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QUALITY-ASSURANCE TESTS OF FIVE Y-12 KEVLAR-49 SPOOLS USED TO FABRICATE STRANDS AND RELIABILITY SPECIMENS FOR STRESS-RUPTURE TESTS

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QUALITY-ASSURANCE TESTS OF FIVE Y-12 KEVLAR† 49 SPOOLS USED TO FABRICATE STRANDS AND RELIABILITY SPECIMENS FOR STRESS-RUPTURE TESTS

INTRODUCTION

An important component of the composite reliability program is the assurance of quality of Kevlar 49*, 380-denier yarn and epoxy-impregnated yarn. This yarn, which is used in the fabrication of W-82 components from Kevlar 49/epoxy composites, is also formed into test specimens for long-term, stress-rupture studies and reliability studies. The QA work covered in this report encompasses preparation of impregnated-yarn specimens, examination of the yarn itself and individual fibers therefrom, tensile testing of bare and impregnated yarns and heat-degraded yarns. The yarn samples were all drawn from spools of 380-denier Kevlar 49 shipped to LLNL from Y-12. The resin matrix is an amine-hardened epoxy with low viscosity and long pot life, intended for filament winding. The components are Dow epoxy resin (DER) 332 and Jeffamine T-403 triamine hardener**. The stoichiometric combining ratio, which we used in our work, is 100 parts by weight resin to 44 parts hardener. Quality-assurance testing not only verifies that the yarns actually meet the manufacturer's specifications, but also provides data on the relationships between fiber characteristics and the lifetime reliability of fabricated items.

OBJECTIVES AND TASKS

o Prepare the following samples and specimens from Y-12-supplied spools of 380-denier Kevlar 49 for QA tests:

  - -Bare yarns for accelerated aging.
  - -Epoxy-impregnated strands (volume fraction of fiber, $v_f = 68 \pm 3\%$)
  - -Filament-diameter samples for obtaining photomicrographs
  - -Filament-count samples for obtaining photomicrographs.
  - -Vol ring specimens for obtaining interlaminar-shear-test samples (v_f =______)

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* Kevlar and Kevlar 49 are registered trade marks of E. I. duPont de Nemours & Co.

**Jeffamine T403 is manufactured by Jefferson Chemical Co., Div. of Texaco.

† Reference to a company or product names does not imply approval or recommendation of the product by the University of California or the U.S. Department of Energy to the exclusion of others that may be suitable.

- o Make the following QA measurements:

  -Denier

  -Filament diameter

  -Filament count

  -Tensile strength of aged (240°C/3 hrs.) and control bare yarns

  -Tensile tests of epoxy-impregnated strands

- o For fiber-aging studies, fabricate strand specimens (v_f = 55 $\pm$ 5%) from humidity- and temperature-conditioned Kevlar-49 spools.

- o For long-term stress-rupture tests, fabricate 5000 strands (v_f = 68 $\pm$ 3%) from Y-12 Kevlar-49 spools.

- o Five Kevlar-49 spools (#0124, 1708, 3208, 4938, 7920) chosen at random from 22 spools received from Y-12 were used for fabricating strands for long-term stress-rupture testing of strands. Reliability specimens will also be made from these spools. Plans are to characterize all fiber that will be used to fabricate reliability specimens. These characterizations will be used to help evaluate test results of reliability specimens.

QA SPECIMEN TAB METHODS AND EXPERIMENTAL DATA

- o Denier measurement - denier is defined as the weight in grams of 9000 meters of yarn or fiber. Denier is determined routinely each time a spool is used to fabricate any specimen. Our denier sample consists of 45 meters of yarn wound onto a special drum (Fig. 1) designed for these measurements, cut off, and weighed to the nearest 0.1 milligram. Table 1 represents calculated denier values determined each time specimens were filament wound from each spool. The average denier is the mean of the determinations made from as many as 8 and as few as 3 samples. DuPont's standard specification for denier is that a roll must not vary more than $\pm$ 6%. From the denier the cross-sectional area of the fiber bundle is determined, as follows:

$$\text{Area}(cm^2) = \frac{\text{denier } (g/9000m)}{9 \cdot 10^5} \cdot \frac{1}{1.44(g/cm^3)}$$

TABLE 1. Denier[a] Measurements

Spool ID	0124	1708	3208	4938	7920
Calculated	381.1	381.8	378.6	381.0	381.9
Denier	381.1	379.2	378.9	381.2	381.9
Values,	381.2	380.7	378.8	381.1	380.9
g/9000m	381.0	380.6	378.2		381.3
		382.6			381.4
					381.1
					381.4
					381.2
Average Denier, g/9000m	381.1	381.0	378.6	381.1	381.4
Standard Deviation, g/9000m	0.08	1.29	0.31	0.10	0.36
Coefficient of Variation, %	0.021	0.339	0.082	0.026	0.094

NOTE: These data represent a precision in the length measurement of 0.016m/45m. Refer to raw data in Table 4.

[a]Denier = weight in grams of 9000m of yarn or fiber, i.e., 200 x the measured weight of a 45-m length.

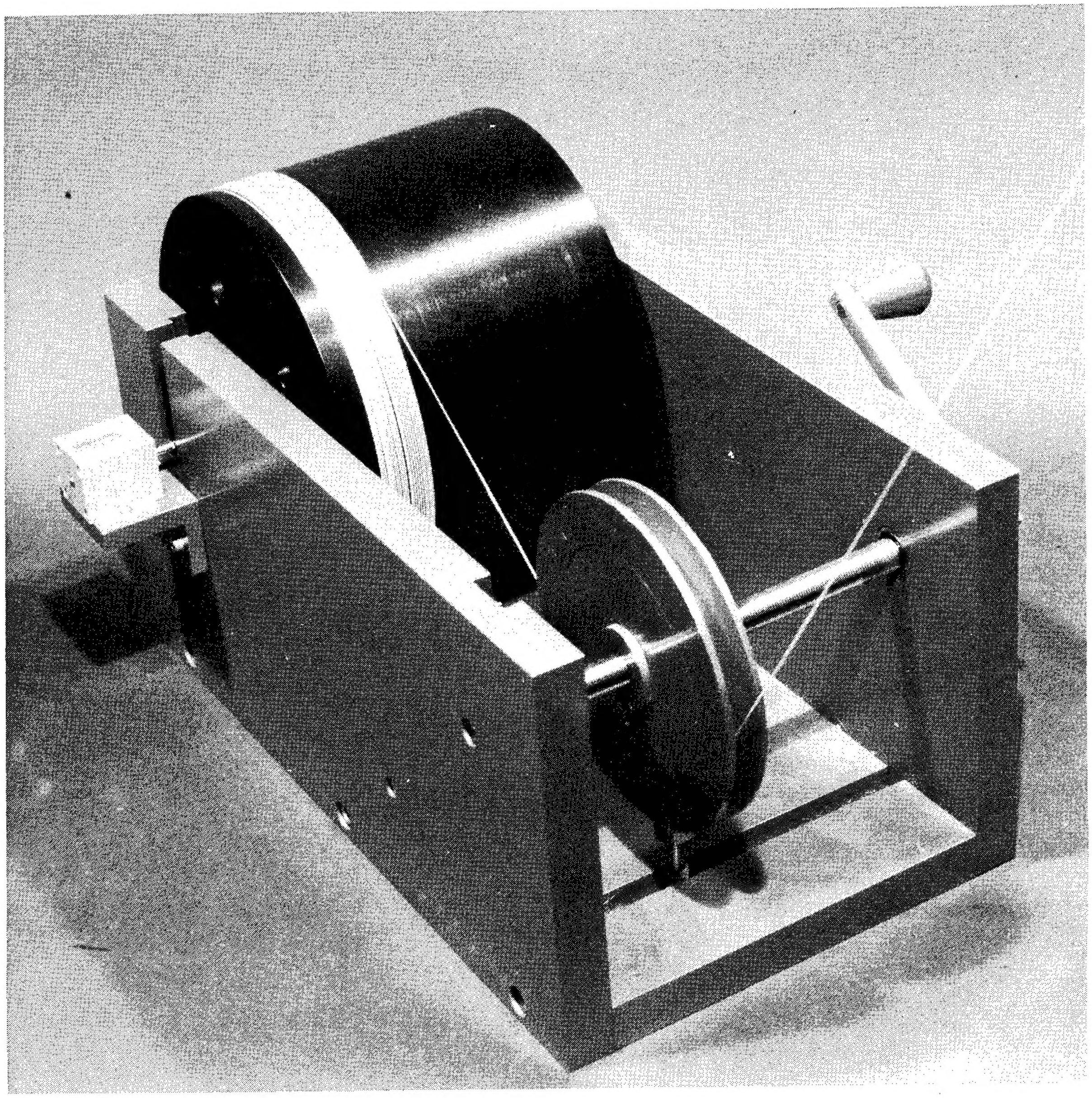

Fig. 1: This device is used to measure accurately 45 meters of 380-denier yarn

o Filament diameters - These are measured on scanning electron-microscope (SEM) photographs. Specimens are prepared by cutting 6.35-mm (1/4-in) segments of yarn from each spool, then attaching them horizontally to aluminum mounts with a film adhesive. The SEM photos shown in Fig. 2 were taken at a nominal magnification of 1200X. On each photo, approximately 14 measurements of diameter (i.e., image-width) were made with a 150-mm scale to the nearest 1/4 mm. These were converted to actual filament diameters by comparing them to a calibrated, photographed reference marker. The equation is

$$\text{Fil. diam } (\mu m) = \text{meas. image width (mm)} \times \frac{\text{marker ref. length } (\mu m)}{\text{marker image length } (\mu m)}$$

We learned later that the marker calibration was incorrect; details are reported in Appendix A. The true value of the ratio in the above equation is 0.4018 and the diameters in Table 2, below, were computed from that value.

Table 2. Filament Diameters

Spool ID	0124		1708		3208		4938		7920	
Measured image widths, mm	29.00	29.00	30.50	30.75	29.50	29.75	29.00	28.75	29.50	29.50
	29.00	30.00	30.75	29.50	30.00	28.75	29.00	29.00	29.00	29.25
	31.00	30.75	30.25	30.25	29.00	29.50	29.75	30.00	29.50	29.00
	28.50	28.75	30.75	30.75	28.75	28.75	29.75	30.00	29.50	29.00
	29.00	29.00	30.25	30.50	28.50	28.75	30.50	29.50	29.50	29.75
	30.00	29.75	29.75	30.00	29.00	28.50	30.00	30.00	29.50	29.50
			29.50	30.25	29.00	29.00	30.25	30.50		
Average image widths, mm	29.48		30.22		29.08		29.81		29.38	
Average filament Diam, μm	11.85		12.14		11.68		11.98		11.80	
Standard Deviations μm	0.33		0.18		0.18		0.24		0.10	
Coefficient of Variation, %	2.8		1.5		1.5		2.0		0.85	

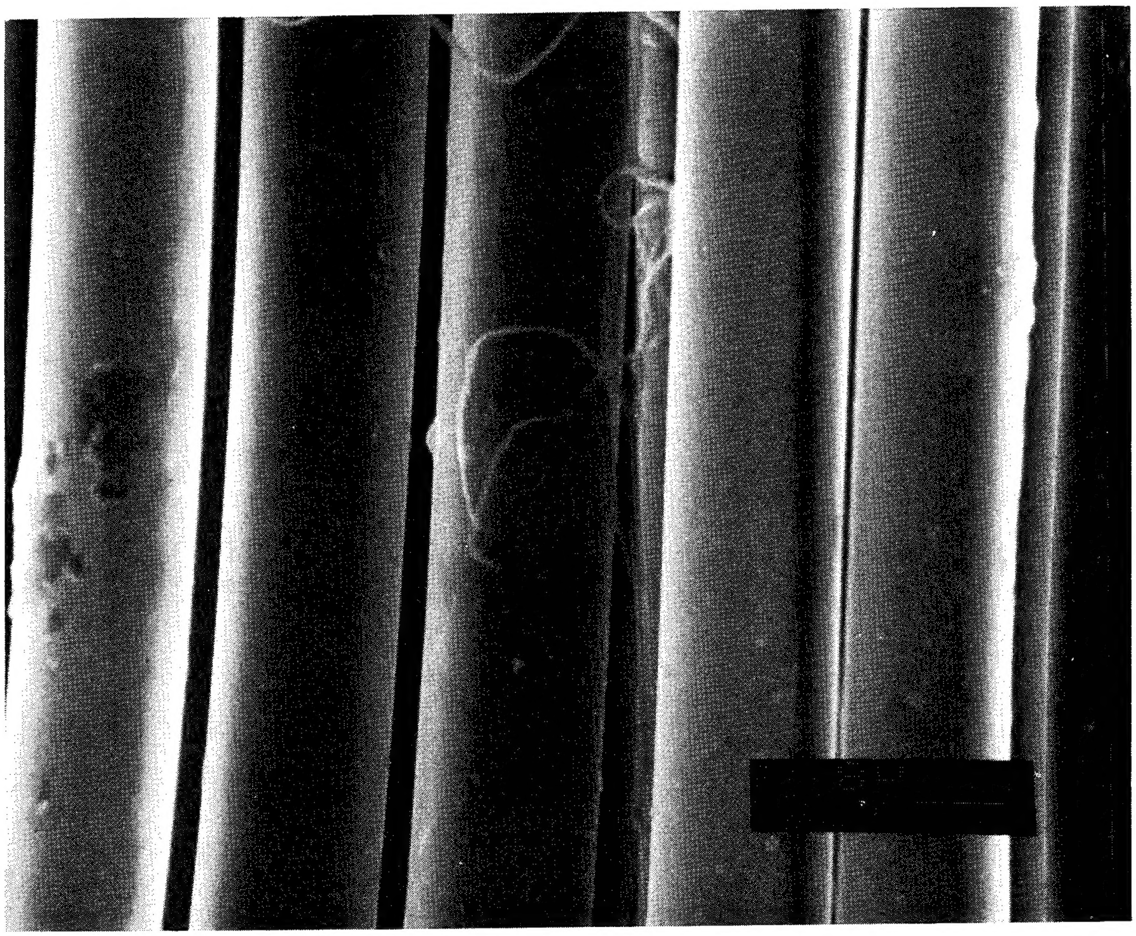

Fig. 2: One of the photomicrographs used in determining filament diameter. Individual fiber cross sections are very nearly circular and are assumed to be exactly so.

- Filament-count specimens are made by cutting short segments from the middle and ends of five epoxy-impregnated strands from a group of strands which have met the required volume-percent-fiber specification. These small segments are potted vertically in a small-diameter hole in a piece of aluminum so they can be polished and photomicrographed. The filament count is made by visually marking off and counting each filament in the photomicrograph. Figure 3 shows typical filament-count photomicrographs. The results are given in Table 3.

- Accelerated aging of bare Kevlar-49 yarn is begun by filament-winding approximately 200 strands onto a rack. The rack is placed in a calibrated air-convection oven for three hours at 240°C. After cooling, the rack is placed on a stand so that an individual yarn can be unwound and attached to a twisting device. The other end (approximately 18.5 in from the twister) is then clamped so that the yarn can be twisted to 4.3 turns per inch of length. While holding the twist in the fiber strand it is clamped, with the aid of an epoxy adhesive, between end-clamps designed especially for tensile testing. Care is taken to maintain the twist during testing. Both the twist and aging parameters are DuPont standards. Figure 4 shows a dry yarn being wound; Figure 5 shows the setup for twisting and clamping the specimen. The adhesive is Epon 828 and hardener, thickened with silica powder to a paste-like consistency. A bead of the adhesive is applied to the center of the clamp so as to embed the yarn. The clamped strand is cured overnight at ambient conditions. The strength data for these yarns are listed in Appendix C and the mean values are in Table 3.

- Specimens of epoxy-impregnated strands that were used in determining tensile strength and lifetime at various loads were fabricated by filament-winding approximately 1000 strands onto a rack (see Fig. 6). The resin was applied by the same method used to wind the reliability specimens. The target loading of resin is 0.41 $\pm$ 0.057 mg/in, to achieve a volume fraction of fiber of 0.68 $\pm$ 0.03 in the impregnated strand. In order to obtain the required number (5000) of strands within that $\pm$ 3% volume-fraction tolerance, many more strands had to be prepared. For the data in this report, 12 racks of 1000 strands/rack were wound. Fig. 6 depicts the strand rack. Strands are qualified by visual inspection as well as by weighing them on an analytical balance to the nearest 0.1 mg.

The weight-tolerance band for 18.5-in-long strands is ± 2 mg for v_f from 65 to 71%. The method used to obtain volume percent fiber is as follows:

1) Multiply the weight of a 45-m length of dry yarn (w_f) by 18.5/(45•39.37) to get the weight of yarn per 18.5-in length.
2) Weigh the epoxy-impregnated strand (w_s).
3) Subtract weight of dry yarn from strand weight.
4) Find volumes of fiber and resin by dividing their weights by their respective densities, 1.44 and 1.15 g/cm^3.
5) Divide the fiber volume by the sum of the volumes and multiply by 100 to obtain volume percent fiber.

These steps may be combined and reduced to the equation

$$v_f\ (\%) = 100/[119.9(w_s/w_f)-0.252].$$

After the measurements reported here (see Appendix D and Table 3) had been completed, we decided that the fiber/resin ratio in the coated strands might be better controlled by drawing the impregnated strand through a small die, thereby squeezing out excess resin. The first dies used were split, to facilitate threading up the strand. However, the die openings are very small and it was difficult to exactly align the two halves of the die. When they were aligned, we obtained cross sections like that in Fig. 3A; when the halves were offset, cross sections like that in Fig. 3B occurred. Late in 1983, a Strand Task Force was set up with the goal of improving control of impregnation, comprised of L. E. Caley, T. T. Chiao, T. S. Ford, R. L. Moore, R. G. Scott and R. J. Sherry. Dan Noecker helped design and build die holders and fiber-massage wheels that improved strand handling. A key improvement was the replacement of split dies with one-piece, diamond-core dies. The successful achievement of all task-force goals was reported in a memorandum by R. J. Sherry on December 19, 1983. With the split dies the standard deviation of volume percent fiber in some typical strands was 1.5 vol% and about 6% of strands were outside the 65 to 71% limits. With the new dies and handling equipment, the standard deviation dropped to 0.25 vol% and all strands were within a band from 68.2 to 69.1 percent.

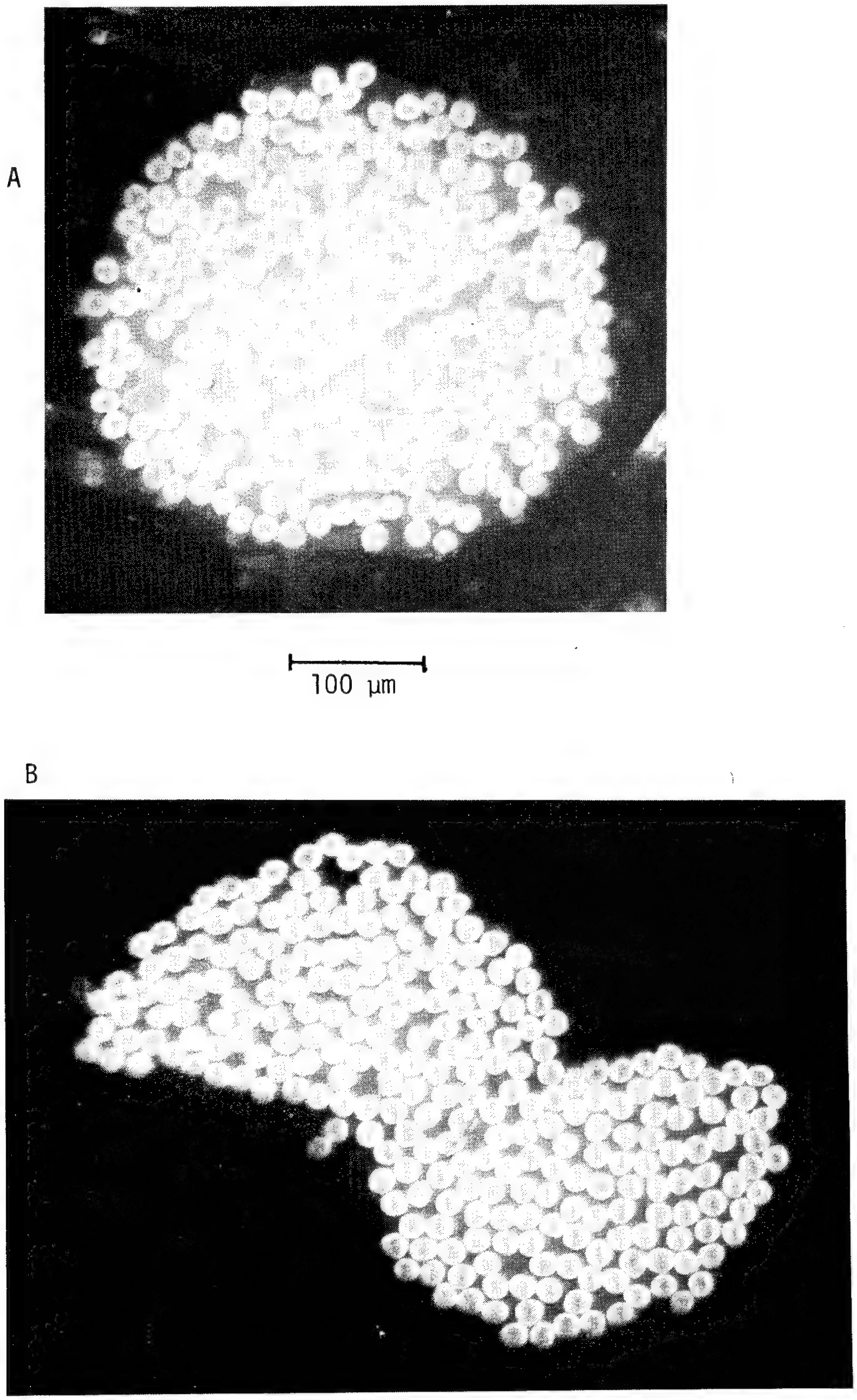

Fig. 3: Optical micrographs of cross sections of impregnated Kevlar 49 strands embedded in an epoxy matrix, cut through and polished. Section A is typical of strands measured in this study. Section B is from a strand produced with a split die when the halves are offset.

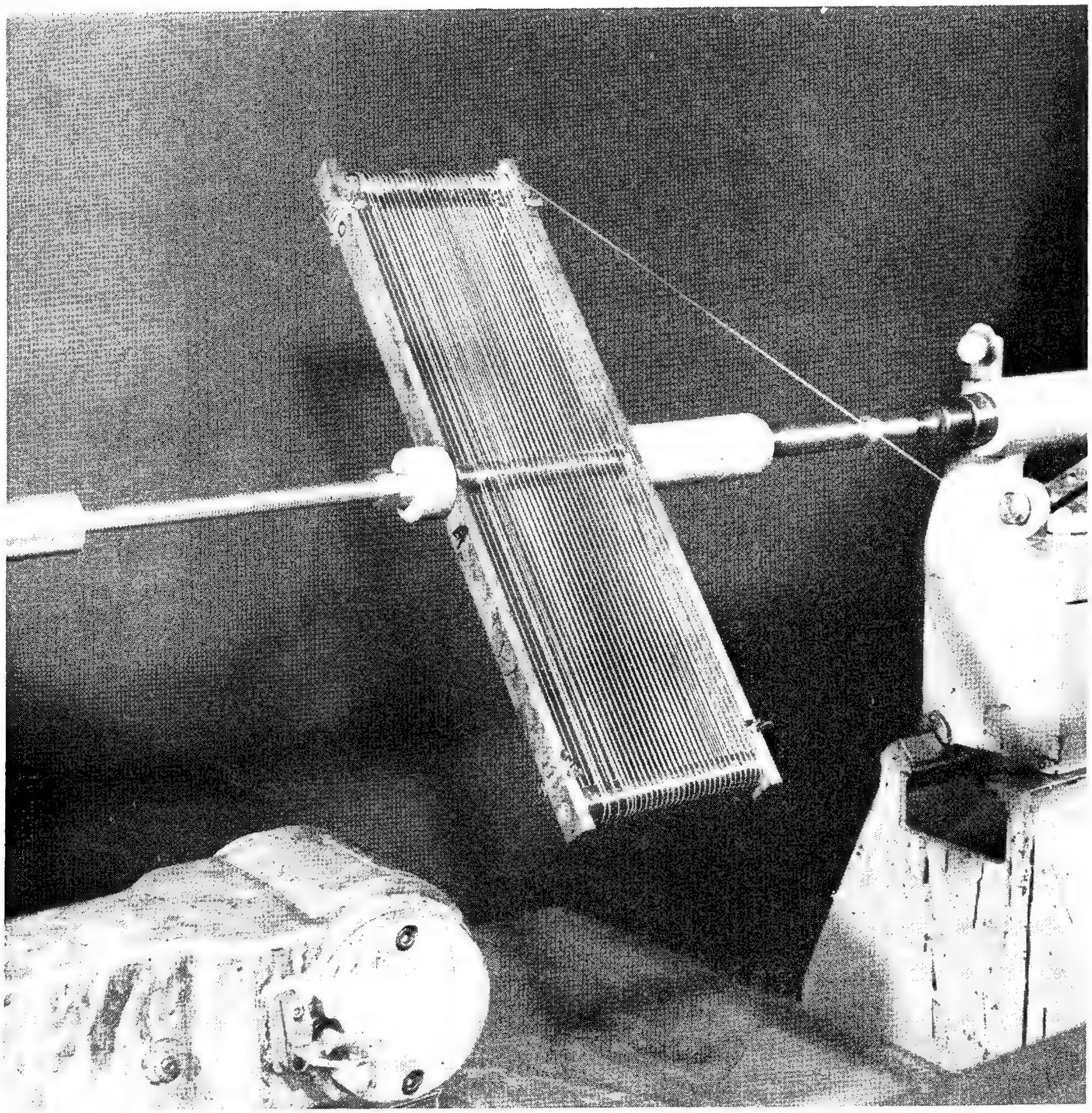

Fig. 4. A single Kevlar strand is wound on a rack to generate about 200 18.5-in lengths for accelerated-aging test.

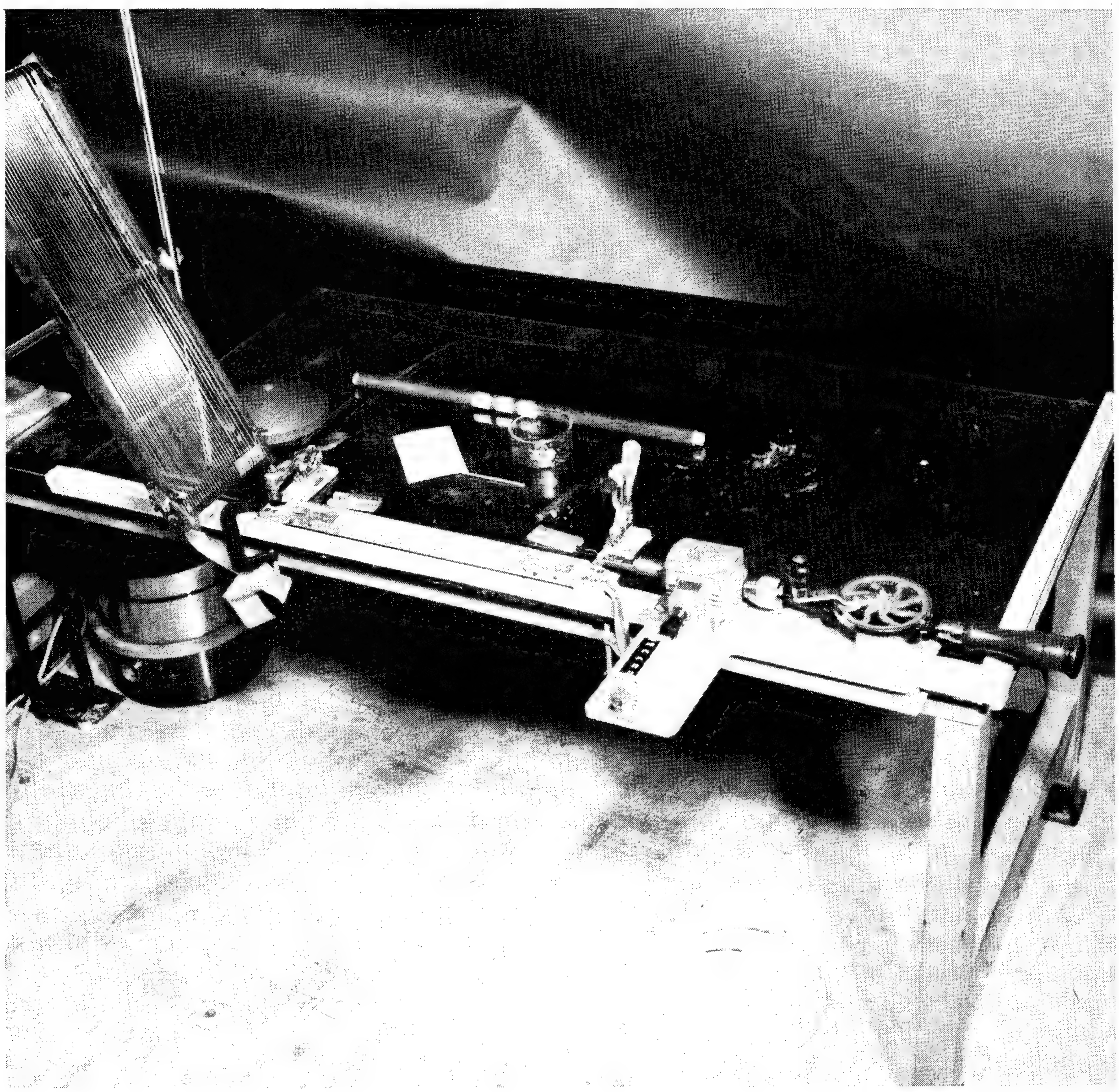

Fig. 5. Both control and degraded Kevlar 49 fiber lengths of 18.5 in are twisted at 4.2 turns/in, clamped between toggle clamps, then end-tabbed using either aluminum or acrylic tensile clamps.

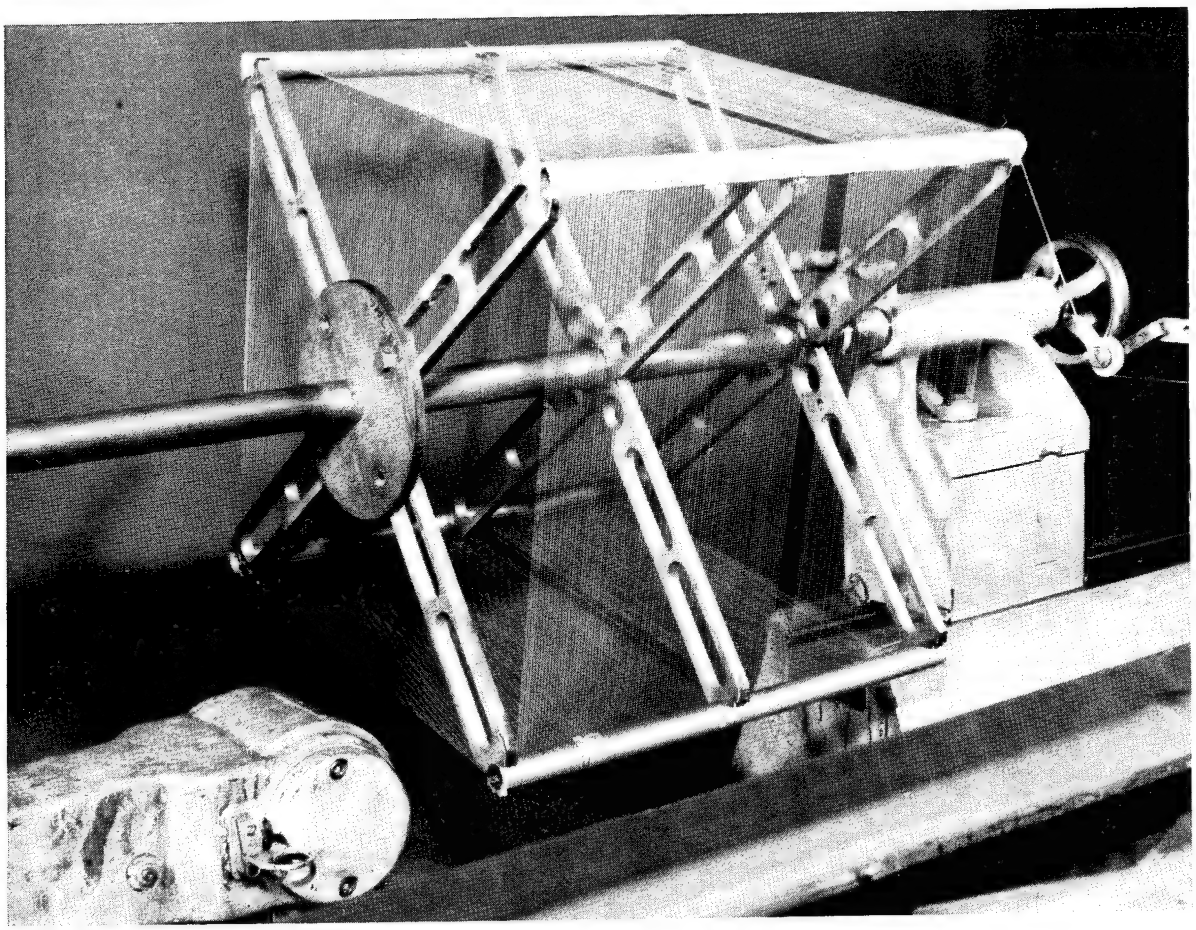

Fig. 6: One thousand tensile strands of Kevlar 49 fiber can be wound onto the rack shown here. The rack of epoxy-impregnated fiber is removed from the filament winder and placed in a convection oven for curing.

SUMMARY DATA TABLE

Table 3 is a summary of all strand data gathered for this study. All raw data for generation of this table appear in the relevant tables in Appendices B through D. The averages for denier, strand diameter and filament count are all very close to the values given in DuPont's data sheet for Kevlar 49, 380-denier yarn, as cited by L. L. Clements in UCID-17873, dated October 10, 1978. The strengths of the bare yarns exceed the DuPont value of 2760 MPa at 24°C, while those for coated strands averaged below the DuPont value of 3620 MPa given for "strands" at 24°C.

TABLE 3

SPOOL ID	0124	1708	3208	4938	7920
Average Denier, g/9000m	381.1	381.0	378.6	381.1	381.4
Cross Sectional Area ($in^2 x 10^{-5}$)	4.56	4.57	4.53	4.56	4.56
($cm^2 x 10^4$)	2.942	2.948	2.923	2.942	2.942
Average Filament Diameter (μm)	11.85	12.14	11.68	11.98	11.80
Average Filament Count, No. Ends/Yarn	267	267	267	267	264
Strength of Control Strands (lb) (Twisted Bare Yarn) Average of 20 Spec.	20.22	19.78	19.91	20.28	19.65
Strength of Degraded Yarn (lb) (3 hrs @ 240°C) Average of 20 Spec.	18.79	19.72	19.75	18.92	18.93
Strength Loss (%)	7.1	0.3	0.8	6.7	3.7
Strength of Epoxy-Impregnated Strands, lb	22.70	22.60	22.40	22.60	22.40
Strength Gain (%) Due to Epoxy-Impregnation	12.27	14.26	12.51	11.44	13.99

DISCUSSION OF DATA

Denier measurements. The actual deniers of these nominally 380-denier yarns are clearly well within the limits of 380 ± 23 specified by DuPont, with coefficients of variation within spools far below the 6% limits (which might well be interpreted as three times the allowable coefficient). It is interesting, however, that one spool, No. 1708, showed a standard deviation of denier of 1.29 g/9000m that was very significantly higher than the other four (by Bartlett's test of variance inhomogeneity). This suggests the presence of unusual process disturbances while spool 1708 was being manufactured.

Another feature of these data that stands out is that the mean denier of No. 3208 is less than the others, which are all very nearly equal. By pooling the variance components from the four homogeneous spools (omitting No. 1708), we get a pooled standard deviation of 0.0751 with 15 degrees of freedom. This can be used in a t-test of the hypothesis that the true mean denier of spool 3208 is 380. The t-value obtained is -42, many times the critical value of 4.07 for a Type-I risk of 0.001. Thus, while spool 3208 has a mean denier within the DuPont limits, it is very definitely below the target by 1.4 g/9000m. This, too, is probably due to some abnormal process condition.

Filament diameters. As with the denier values, there is again evidence in the diameter data of variance inhomogeneity as well as inhomogeneity among the means. Bartlett's test fails at the risk level 0.01, mainly because of the high and low standard deviations of spools 0124 and 7920, respectively. But, even taking the largest one, 0.33 μm, as the most conservative gauge of differences between spools, the standard error of the difference between spool means is 0.12 and twice that value is 0.24 μm. Only occasionally would one expect two of these means to differ by this much, and the only two that do are those for Spools 1708 and 3208, which differ by 0.46 μm. However, 1-way analysis of variance shows that the differences among means are significant at the 99% level, though not large percentagewise. They seem to fall into two clusters, Spools 0124, 3208 and 7920, averaging 11.78 and the other two, averaging 12.06 μm. The difference, 0.28, is only about 2.3% of the overall mean.

Strengths. The strengths reported in Table 4 are supported by tables and plots in Appendix B. That appendix is organized according to, first, the state and test condition and, second, according to spool number. Each data table is accompanied by a composite plot of load vs. strain for the 20 or more strands included in the table. Beneath each plot is a statistical summary for the sample that includes the following items:

mean rupture load, lb, and coefficient of variation, percent
mean deflection at rupture, in/in, and CV
mean modulus at rupture, lb/(in/in), and CV
mean load at strain = 0.002, lb, and CV
mean load at strain = 0.004, lb, and CV
number of specimens included in test statistics

In making such tests, one finds that, of 20 strands tested, from none to several will break at one of the grips. Since such a break may have been caused by some anomaly in applying the grip, those strands are excluded from the tables and statistics regardless of their measured values.

For the unimpregnated yarns, the rupture loads may be converted to ultimate tensile strengths (UTS) by dividing by the cross-sectional areas of the strands. As was mentioned earlier, these areas are most accurately obtained from the deniers. Taking Kevlar 49 density to be 1.43 g/cm^3--as we measured it--and using the mean denier of 381 g/9000m, the mean cross section is $2.96 \cdot 10^{-4} cm^2$. A pound-force = 4.448 N. UTS is given by

$$\text{UTS} = 150.3\ L\ (\text{MPa})\ \text{or}\ 21.80\ L\ (\text{kpsi})$$

where L is the mean rupture load in pounds. The same factors apply to the modulus values.

The rupture-load data were subjected to some further statistical analysis to determine if differences among spools and treatments are real. For this purpose the rupture-load means and standard deviations have been collected in Table 5. On glancing over this table, one perceives that, within each treatment group the spool means seem pretty homogeneous while those for the degraded strands and the coated strands appear definitely lower and higher, respectively, than those for the bare strands, as might be expected. The standard deviations appear to be more scattered. In the bare-strand group,

TABLE 4: STRENGTH SUMMARY

A. Bare strands

Spool Nbr.	Rupture Load, Lb Mean	Rupture Load, Lb Std. Dev'n	Number of Specimens Included
0124	20.22	0.4236	18
1708	19.78	1.0576	19
3208	19.91	0.5095	18
4938	20.28	0.4200	20
7920	19.65	0.6050	15
B. Degraded strands			
0124	18.79	1.9466	20
1708	19.72	0.7089	19
3208	19.75	0.4736	18
4938	18.92	1.6368	20
7920	18.93	0.6548	16
C. Coated strands at room temperature			
0124	22.74	0.7982	18
1708	22.55	1.4218	20
3208	22.43	1.6827	19
4938	22.50	0.8975	19
7920	22.41	1.3941	37

the standard deviation for Spool 1708 is much higher than the others. This inflation was traced to two low strength values, the last two in the table on p 27. Without these two values, the 1708 standard deviation drops to 0.6649 lb and the group appears homogeneous in variance.

With the degraded strands, there is definite variance inhomogeneity not due to a few outlying strengths. For the coated strands there is borderline inhomogeneity. For the three groups, the pooled standard deviations are 0.5266, 1.2711 and 1.3076 lb, respectively. Clearly, the processes of prolonged heating in air and epoxy-impregnation introduce variability not present in the bare strands.

Analysis of the within-group differences among spools show that they are not significant. That means, for example, that all the bare-strand strengths of the spools may be viewed as arising from a single distribution of bare-strand strength with a common mean of 19.97 lb and a common standard deviation of 0.53 lb. Similarly, for the degraded strands, the values are 19.22 and 1.62 (but possibly as high as 2.00) and for the coated strands 22.51 and 1.31 lb. These values may be converted to strengths in MPa or kpsi by the equations given above.

Further testing shows that the between-group differences in rupture load are highly significant. The degradation treatment reduces the bare-strand strengths by 0.75 lb ($\pm$ 0.30, 95% CL's), while epoxy-impregnation, not surprisingly, increased rupture load by 2.54 $\pm$ 0.28 lb or 11.6%. This enhancement is somewhat more than can be attributed to the load carried by the epoxy filling 32% of the cross section, suggesting that the binding effect of the epoxy resin is helping the stronger Kevlar filments to support the weaker ones.

Elongations and moduli. Differences among the mean elongations could be analyzed in the same way that the rupture loads were, with similar, though probably not identical, conclusions. Beneath the load/elongation plots in Appendices B, C and D we have listed the mean breaking loads, the mean elongations at break and the mean moduli at rupture, along with the corresponding coefficients of variation. Upon leafing through those listings, the reader will notice two prevailing features: (1) when the rupture loads showed high or low variability, so did the elongations; (2) the coefficients of variation for the moduli are invariably lower than those of load and elongation. The modulus (E) is calculated as the quotient of load (L) divided by elongation (e), i.e., $E = L/e$. If L and e were independent random variables, variance-propagation theory tells us that the coefficient of variation of E would be given by

$$CV_E = [CV_L^2 + CV_e^2]^{0.5}$$

But if L and e are positively correlated, CV_E will be smaller than this value, which must be larger than either CV_L or $/CV_e$. If the correlation is strong, CV_E can be less than either of the others, as is the case in all fifteen of our data sets. The weakest correlation among these is exhibited by the data pairs for Spool 4938 bare strands (p 31), while the the strongest occurs with Spool 7920 coated strands (p 55). In the latter case, as the plot in Figure 7 shows, the correlation is very tight, with r = +0.9947.

To see why this occurs, recall that the elastic modulus is the governing and fundamental material property for the 267 filaments of the strand. Local imperfections in filaments can reduce strength substantially but the modulus is unaltered. The elongation is actually dependent on strength through the modulus, e = L/E, so when a strand fails at low load, the elongation reached is low, too, and vice versa.

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This study was conducted as part of the composites-reliability program, under the direction of Satish V. Kulkarni. We gratefully acknowledge the advice and consultation of T. T. Chiao regarding fabrication and testing of the quality-assurance specimens. We are especially grateful to Dr. Marilyn Wardle and Technician David Erickson of DuPont for showing us their split-die method for impregnating Kevlar strands with epoxy resin. This led us to the one-piece-die concept.

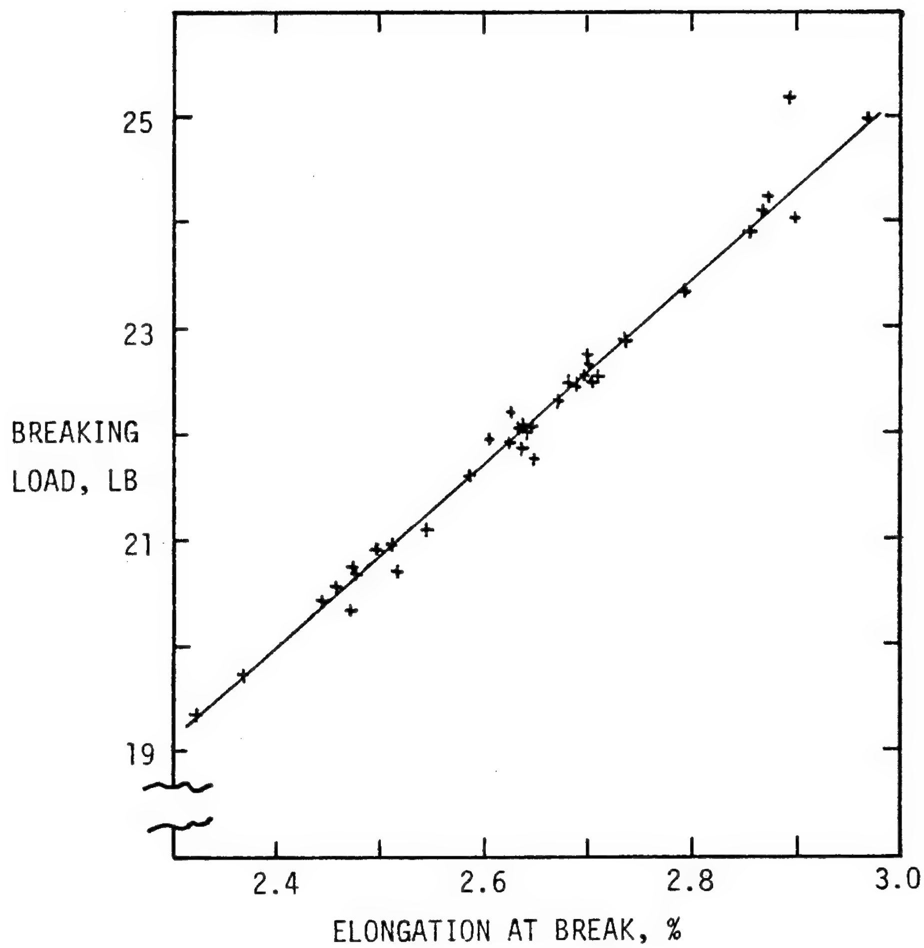

Fig. 7: For 37 coated strands from Spool 7920, load and elongation at rupture are intimately correlated.

APPENDIX A
Diameter Measurements

It is a straightforward calculation to estimate the yarn denier from the mean filament diameter, filament count per yarn, and polymer density (or to estimate diameter from denier). As Fig. 3 shows, the filaments are very nearly circular in cross section; on the average, assuming them to be circular involves negligible error. The equation is

$$D = 0.007069\ d^2\ C\ \rho \quad (\text{g}/9000\text{m})$$

where
d = mean filament diameter, μm
C = filaments per yarn
ρ = polymer density, g/cm^3

When the original SEM filaments measurements were used to estimate denier according to this equation, taking the density to be the published value of 1.44 g/cm^3, all five deniers came out too high, by an average of 16%. The denier measurements are quite simple and accurate, so we looked for possible biases in filament diameter and density.

Two balls of yarn weighing about 6 g each were wound from spool 7920 and another, unidentified spool. The densities were measured with a Beckmann powder pycnometer and found to be 1.416 and 1.436 g/cm^3, respectively, within 1.7% of the nominal value.

Diameters of filaments from spool 7920 were remeasured by optical photomicrography in the following way. About one-third of the area of the embedded 7920 yarn was photographed at 800X (Fig. A1). This photo contains 79 whole cross sections. These were measured by the Zeiss procedure, which compares each filament cross section to that of a circle of the same area, then reports the filament size as the diameter of that equivalent circle. Since these filaments are nearly circular, these sizes should be both accurate and ideal for the immediate purpose. With the same microscope setup, a photograph was taken of a certified stage micrometer, Fig. A2. By measuring this with a good steel scale, we learned that the 25-μm gauge length shown

on Figs. A1 and A2 was actually 24.5 μm long. When this correction was applied to the 79 Zeiss diameters, the corrected mean value was 12.06 with a standard error of 0.06 μm. For spool 7920 the filament count was 264/yarn (Table 4). When these numbers and the density of 1.416 g/cm^3 are inserted into the above equation, the estimated denier is 384.3 g/9000m, only 0.8% more than the measured value, well within the errors of diameter and density measurement. The difference is, however, larger than the reasonable error for the direct measurement of denier. It appears that one can get a more accurate estimate of <u>mean</u> filament diameter from the measured denier than by direct measurement, though this sheds no light on the local variability of individual filament diameters.

We concluded that the marker reference length used in the SEM work was too low by 8.0%. The filament diameters obtained in that work and listed in Table 2 include that correction.

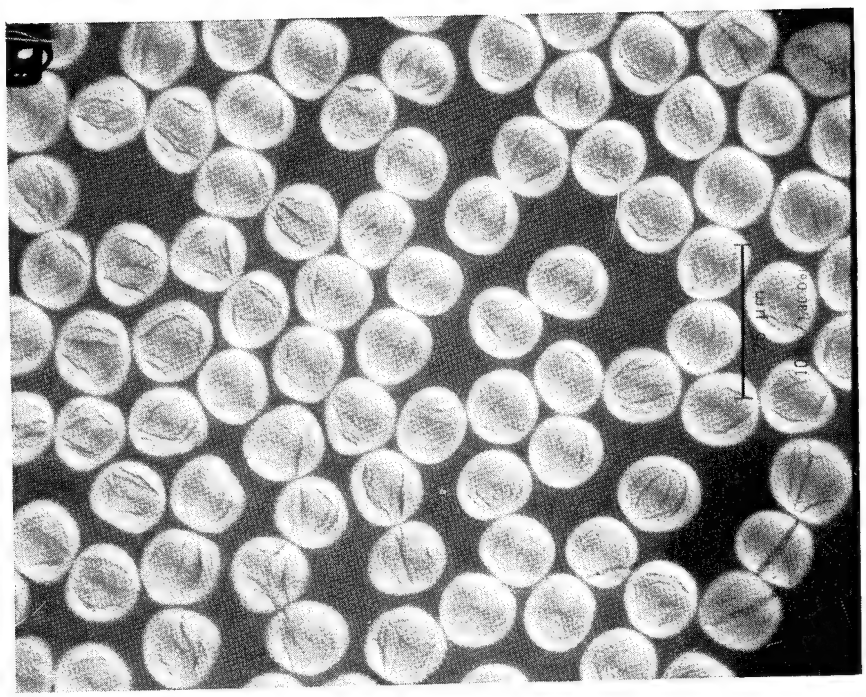

Fig. A1: Optical micrograph at 800X of embedded cross section of 7920 yarn. The 79 whole filament cross sections were measured by Zeiss method described in text.

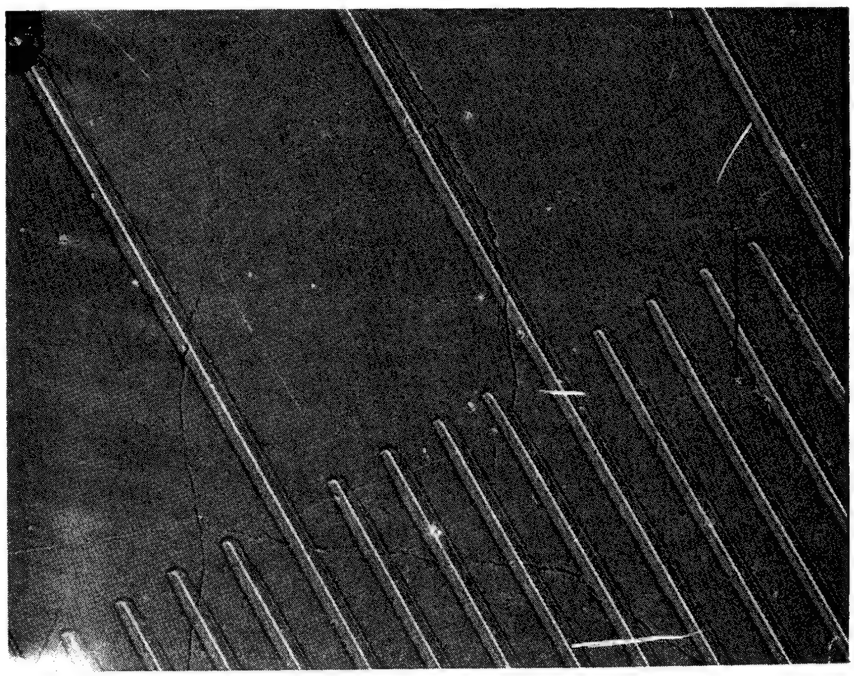

Fig. A2: Optical micrograph of stage micrometer taken at same settings as Fig.A1. True distance between markings is 10 μm, so the 25-μm marker is actually 24.5 μm long.

APPENDIX B

BARE-STRAND TEST DATA

K49 SPOOL 0124 CONTROL TWIST 4.2 TPI

Test ID	Max. Load,Lb	Strain at Max, %
1945041	19.73	2.502
1945043	19.70	2.439
1945044	20.11	2.475
1945045	20.12	2.538
1945046	20.19	2.442
1945047	20.05	2.498
1945048	20.77	2.600
1945049	19.77	2.442
1945050	20.24	2.473
1945050	19.61	2.433
1945051	20.99	2.540
1945052	20.16	2.516
1945052	20.71	2.475
1945052	19.76	2.451
1945056	20.81	2.514
1945058	20.55	2.557
1945058	20.16	2.411
1945060	20.55	2.577

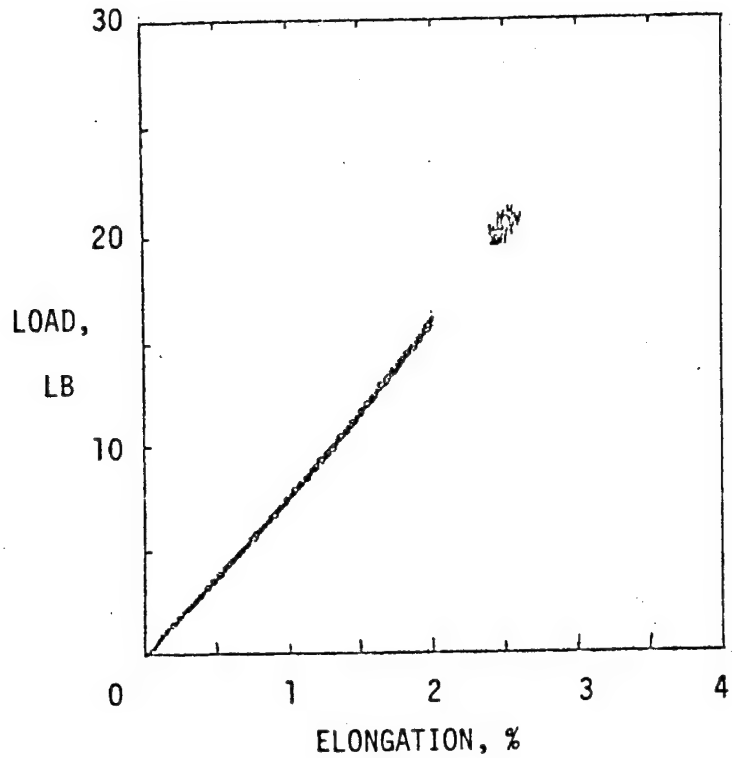

Fig. B1: Composite curve for Spool 0124 bare strands, 18 specimens. Group statistics are:

Property	Mean	CV,%
Rupture load, lb	20.22	2.095
Deflection at rupture, %	2.494	2.156
Modulus at rupture, lb/(in/in)	811.1	1.778

K49 SPOOL 1708 CONTROL TWIST 4.2 TPI

Test ID	Max. Load,Lb	Strain at Max, %
1945141	19.71	2.289
1945142	20.70	2.494
1945143	18.37	2.407
1945144	20.56	2.450
1945145	19.95	2.304
1945146	20.90	2.446
1945147	20.69	2.454
1945148	20.90	2.394
1945149	19.82	2.366
1945150	19.95	2.355
1945151	20.44	2.370
1945152	20.28	2.415
1945153	20.00	2.312
1945154	20.62	2.338
1945155	19.06	2.257
1945156	18.97	2.236
1945157	18.78	2.379
1945158	19.80	2.466
1945159	17.26	2.173
1945160	17.47	2.094

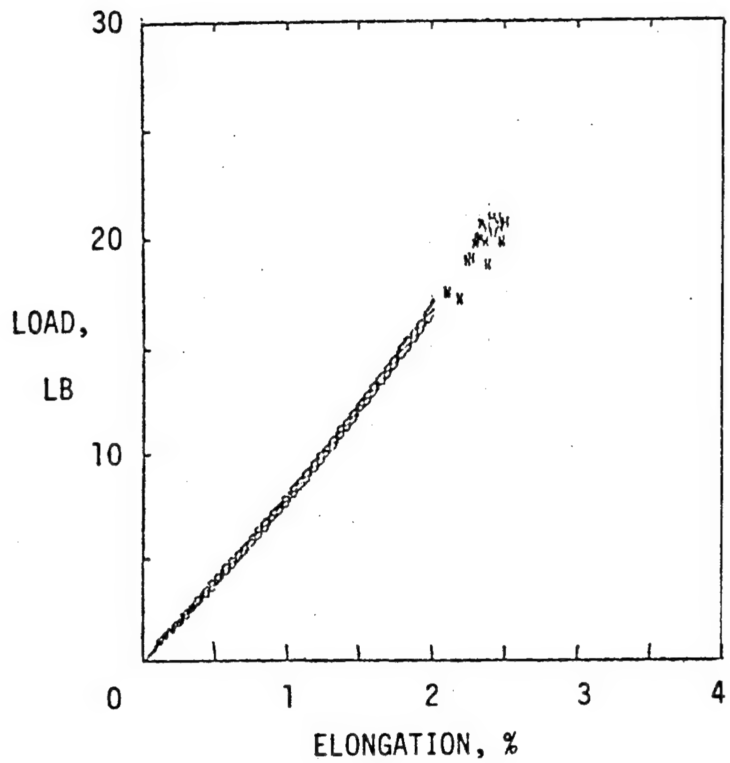

Fig. B2: Composite curve for Spool 1708 bare strands, 19 specimens. Group statistics are:

Property	Mean	CV,%
Rupture load, lb	19.78	5.347
Deflection at rupture, %	2.347	4.464
Modulus at rupture, lb/(in/in)	842.5	2.986

K49 SPOOL 3208 CONTROL TWIST 4.2 TPI

Test ID	Max. Load,Lb	Strain at Max, %
1945001	19.54	2.413
1945001	20.26	2.452
1945003	19.39	2.389
1945004	20.43	2.510
1945005	18.93	2.353
1945006	20.13	2.476
1945007	20.35	2.518
1945008	20.45	2.563
1945009	20.66	2.577
1945010	19.14	2.356
1945011	19.45	2.430
1945012	19.76	2.462
1945013	19.32	2.346
1945014	20.38	2.559
1945015	20.09	2.506
1945016	19.82	2.509
1945017	20.06	2.507
1945018	20.38	2.509
1945019	19.50	2.461
1945020	20.14	2.508

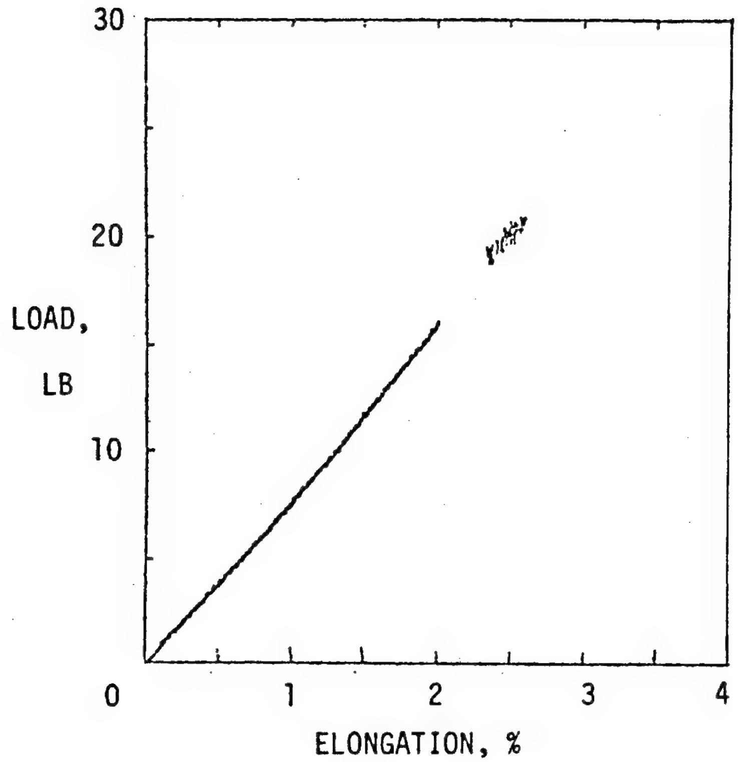

Fig. B3: Composite curve for Spool 3208 bare strands, 18 specimens. Group statistics are:

Property	Mean	CV,%
Rupture load, lb	19.91	2.559
Deflection at rupture, %	2.472	2.582
Modulus at rupture, lb/(in/in)	805.7	0.993

K49 SPOOL 4938 CONTROL TWIST 4.2 TPI

Test ID	Max. Load,Lb	Strain at Max, %
1945020	19.97	2.608
1945022	20.08	2.487
1945023	20.69	2.701
1945024	19.56	2.514
1945024	20.98	2.628
1945026	20.94	2.738
1945027	19.99	2.605
1945028	20.45	2.533
1945029	20.28	2.606
1945020	20.23	2.598
1945021	19.51	2.432
1945032	20.64	2.602
1945033	20.32	2.064
1945034	20.57	2.543
1945035	20.51	2.599
1945036	19.95	2.475
1945037	20.56	2.545
1945038	20.53	2.543
1945039	20.20	2.565
1945040	19.67	2.540

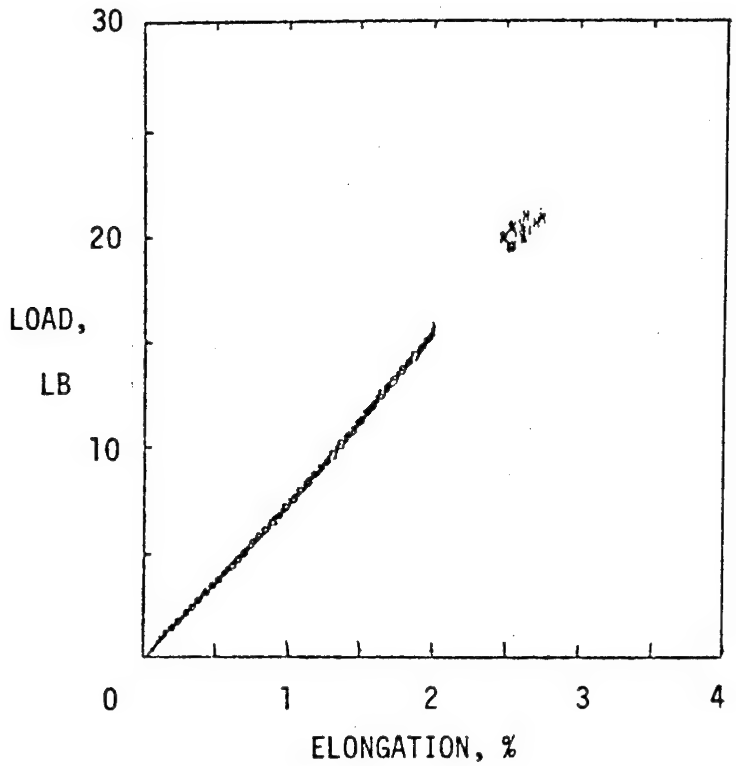

Fig. B4: Composite curve for Spool 4938 bare strands, 20 specimens. Group statistics are:

Property	Mean	CV,%
Rupture load, lb	20.28	2.071
Deflection at rupture, %	2.580	2.550
Modulus at rupture, lb/(in/in)	786.4	2.125

K49 SPOOL 7920 CONTROL TWISTED 4.2 TPI

Test ID	Max. Load,Lb	Strain at Max, %
1928004	19.58	2.487
1928005	20.72	2.622
1928006	20.67	2.630
1928007	19.81	2.466
1928009	19.24	2.398
1928010	19.25	2.453
1928011	19.22	2.459
1928012	19.90	2.564
1928013	18.53	2.364
1928014	20.34	2.656
1928075	19.74	2.501
1928076	19.11	2.444
1928078	19.96	2.547
1928079	19.33	2.481
1928080	19.33	2.441

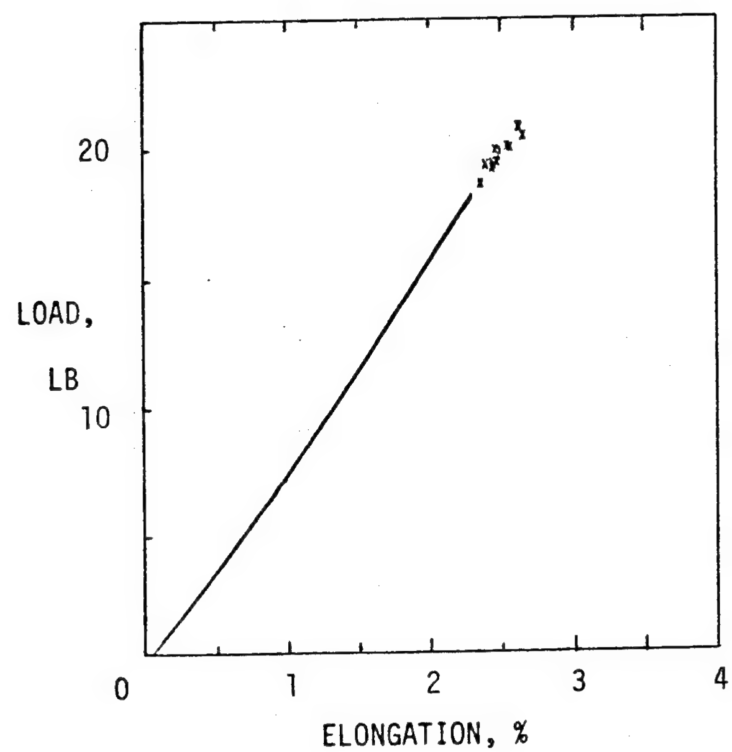

Fig. B5: Composite curve for Spool 7920 bare strands, 15 specimens. Group statistics are:

Property	Mean	CV,%
Rupture load, lb	19.65	3.075
Deflection at rupture, %	2.501	3.439
Modulus at rupture, lb/(in/in)	785.9	1.194

APPENDIX C

DEGRADED-STRAND TEST DATA

K49 SPOOL 0124 3H 240C TWISTED 4.2 TPI

Test ID	Max. Load,Lb	Strain at Max, %
1945121	20.34	2.516
1945122	17.45	2.080
1945123	20.35	2.335
1945124	20.69	2.458
1945125	15.60	1.897
1945126	17.13	2.012
1945127	17.82	2.114
1945128	19.91	2.428
1945129	19.37	2.330
1945130	19.65	2.365
1945131	19.90	2.347
1945132	19.68	2.334
1945133	19.01	2.208
1945134	16.39	1.933
1945135	20.44	2.421
1945136	17.91	2.040
1945137	13.63	1.725
1945138	20.77	2.459
1945139	19.11	2.296
1945140	20.67	2.522

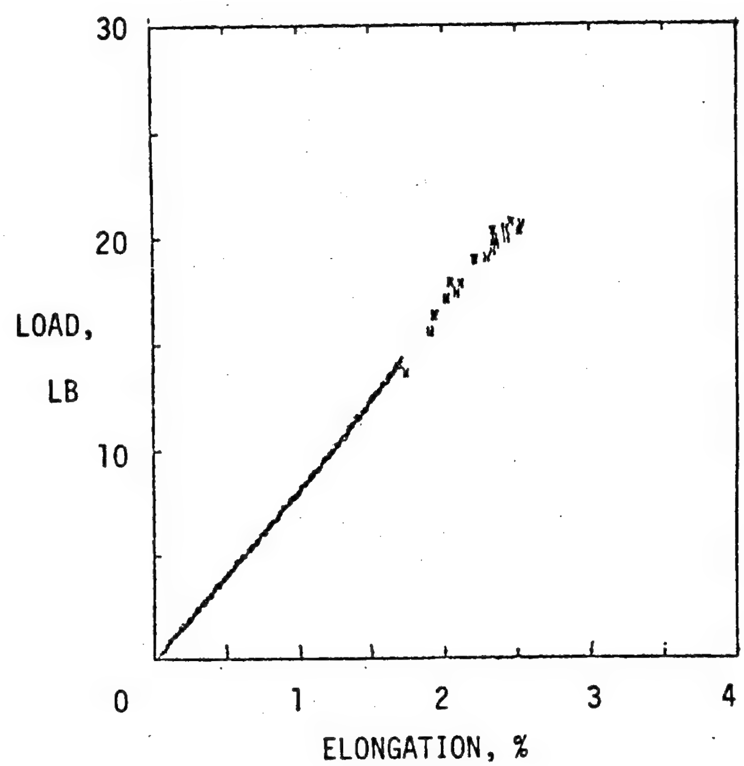

Fig. C1: Composite curve for Spool 0124 degraded strands, 20 specimens. Group statistics are:

Property	Mean	CV,%
Rupture load, lb	18.79	10.36
Deflection at rupture, %	2.241	10.17
Modulus at rupture, lb/(in/in)	838.4	2.440

K49 SPOOL 1708 3H 240C TWISTED 4.2 TPI

Test ID	Max. Load,Lb	Strain at Max, %
1945101	19.45	2.330
1945102	19.26	2.272
1945103	18.27	2.142
1945104	19.71	2.405
1945105	19.92	2.306
1945106	19.85	2.336
1945107	19.68	2.404
1945108	16.21	2.001
1945109	19.27	2.281
1945110	19.93	2.357
1945111	19.48	2.277
1945112	19.23	2.245
1945113	21.07	2.613
1945114	19.75	2.409
1945115	20.57	2.491
1945116	18.49	2.260
1945117	21.03	2.547
1945118	20.21	2.504
1945119	19.62	2.307
1945120	19.94	2.447

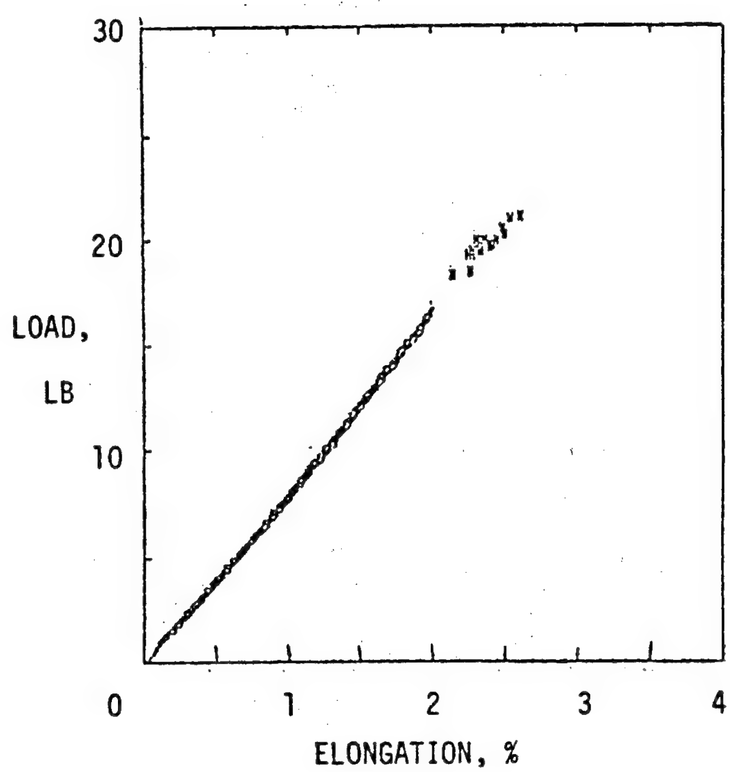

Fig. C2: Composite curve for Spool 1708 degraded strands, 19 specimens. Group statistics are:

Property	Mean	CV,%
Rupture load, lb	19.72	3.595
Deflection at rupture, %	2.355	4.976
Modulus at rupture, lb/(in/in)	834.7	2.204

K49 SPOOL 3208 3H 240C TWISTED 4.2 TPI

Test ID	Max. Load,Lb	Strain at Max, %
1945060	19.68	2.491
1945060	18.36	2.369
1945063	18.68	2.331
1945064	19.52	2.466
1945064	20.07	2.533
1945066	20.19	2.486
1945067	18.61	2.403
1945067	20.38	2.602
1945069	19.86	2.515
1945070	20.39	2.614
1945071	19.22	2.401
1945072	20.09	2.513
1945073	19.99	2.596
1945074	20.25	2.572
1945075	20.11	2.584
1945075	20.19	2.586
1945076	20.41	2.571
1945076	19.92	2.563
1945079	19.16	2.490
1945080	20.42	2.630

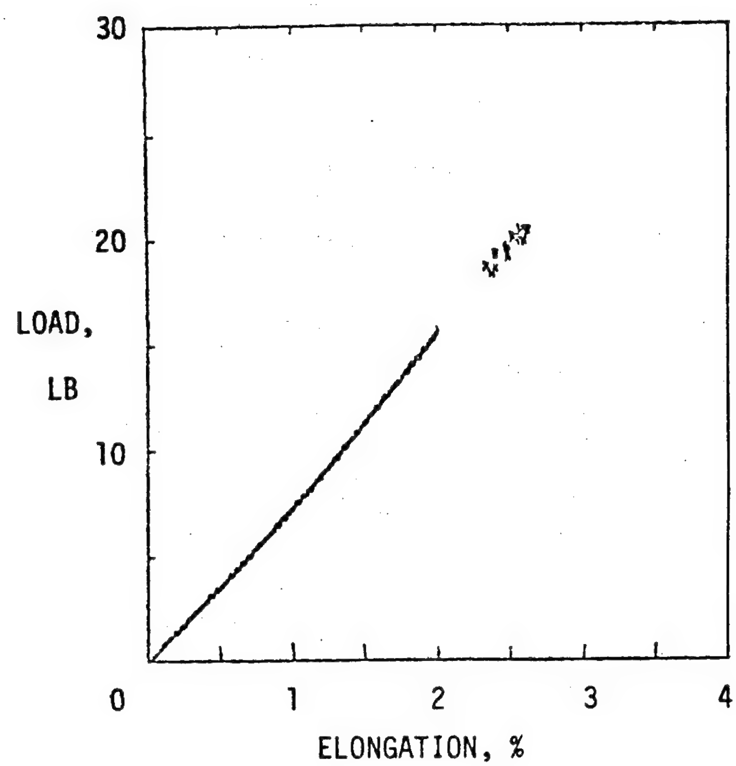

Fig. C3: Composite curve for Spool 3208 degraded strands, 18 specimens. Group statistics are:

Property	Mean	CV,%
Rupture load, lb	19.75	2.398
Deflection at rupture, %	2.517	3.608
Modulus at rupture, lb/(in/in)	784.5	1.324

K49 SPOOL 4938 3H 240C TWISTED 4.2 TPI

Test ID	Max. Load,Lb	Strain at Max, %
1945081	19.80	2.355
1945082	19.65	2.304
1945083	20.18	2.428
1945084	19.80	2.310
1945085	18.81	2.169
1945086	18.89	2.293
1945087	19.04	2.210
1945088	19.13	2.239
1945089	19.95	2.368
1945090	20.13	2.336
1945091	19.03	2.215
1945092	19.56	2.314
1945093	19.71	2.342
1945094	19.82	2.369
1945095	18.96	2.177
1945096	13.03	1.862
1945097	19.29	2.305
1945098	19.15	2.307
1945099	18.23	2.234
1945100	16.19	1.892

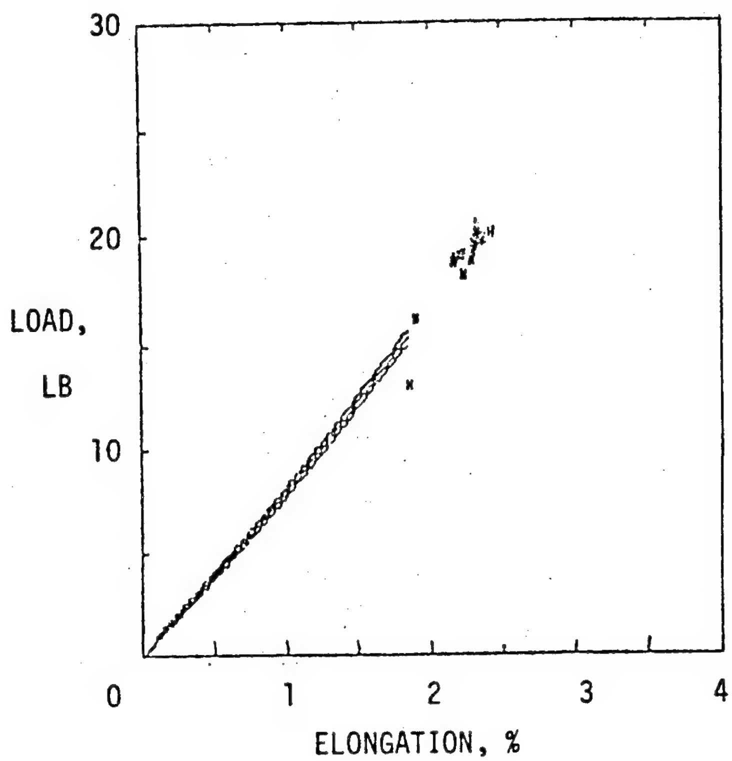

Fig. C4: Composite curve for Spool 4938 degraded strands, 20 specimens. Group statistics are:

Property	Mean	CV,%
Rupture load, lb	18.92	8.651
Deflection at rupture, %	2.251	6.438
Modulus at rupture, lb/(in/in)	839.3	4.228

K49 SPOOL 7920 3H 240C TWISTED 4.2 TPI

Test ID	Max. Load,Lb	Strain at Max, %
1928015	18.85	2.312
1928016	18.89	2.294
1928017	18.51	2.278
1928018	19.20	2.360
1928019	18.74	2.328
1928021	18.26	2.244
1928022	20.10	2.473
1928023	19.07	2.329
1928024	18.09	2.237
1928026	20.18	2.461
1928027	18.10	2.196
1928028	18.63	2.273
1928029	18.87	2.303
1928030	19.27	2.327
1928031	18.30	2.169
1928033	19.80	2.374

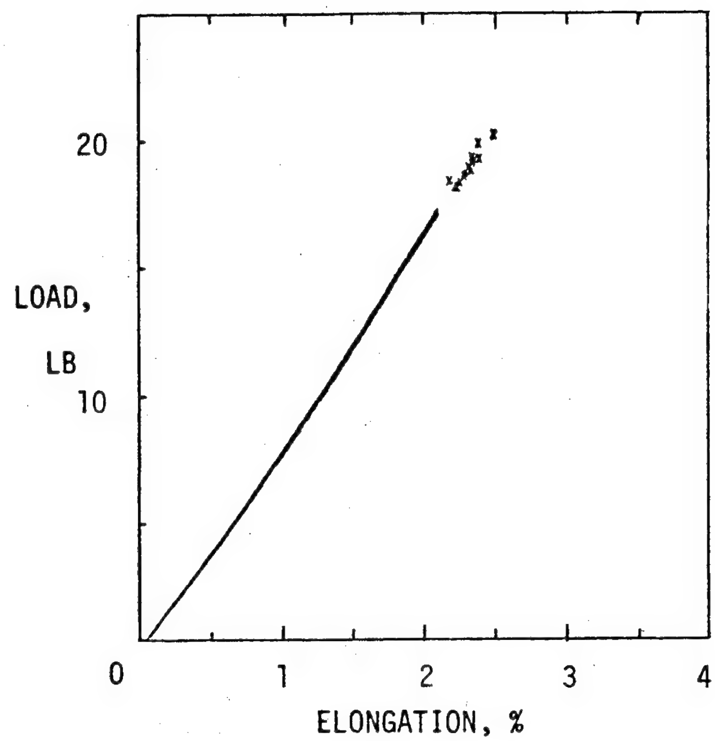

Fig. C5: Composite curve for Spool 7920 degraded strands, 16 specimens. Group statistics are:

Property	Mean	CV,%
Rupture load, lb	18.93	3.459
Deflection at rupture, %	2.310	3.464
Modulus at rupture, lb/(in/in)	819.6	1.186

APPENDIX D

COATED-STRAND TEST DATA

K49 SPOOL 0124 Q.A. BASELINE

Test ID	Max. Load,Lb	Strain at Max, %
2015001	22.78	2.534
2015002	22.88	2.580
2015003	24.47	2.805
2015004	22.85	2.529
2015005	24.26	2.699
2015006	21.77	2.438
2015007	21.99	2.469
2015008	22.31	2.522
2015009	23.04	2.568
2015010	21.01	2.405
2015011	22.72	2.586
2015012	22.45	2.497
2015013	22.52	2.621
2015014	22.52	2.584
2015015	22.38	2.559
2015017	22.97	2.617
2015018	23.18	2.660
2015020	23.15	2.624

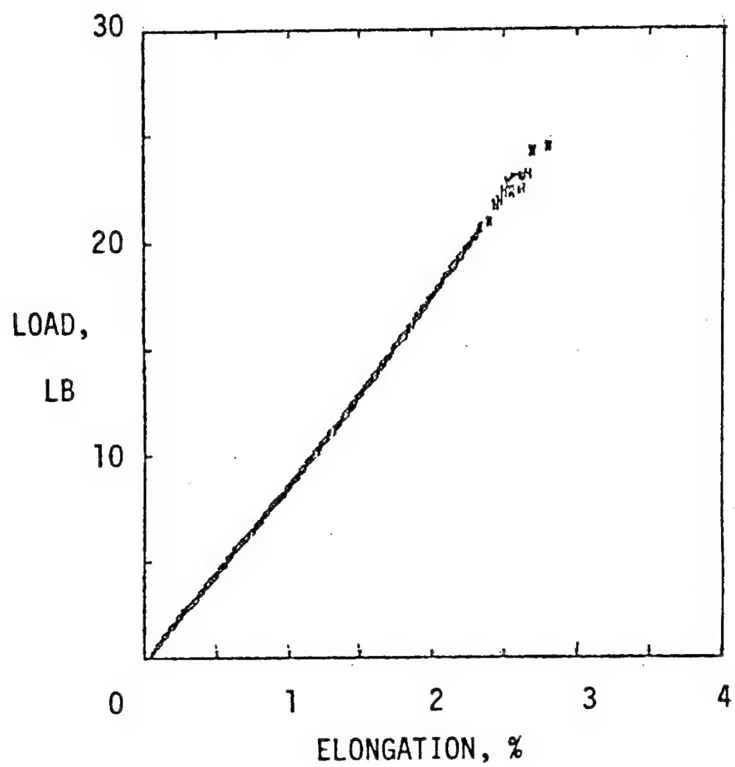

Fig. D1: Composite curve for Spool 0124 coated strands, 18 specimens. Group statistics are:

Property	Mean	CV,%
Rupture load, lb	22.74	3.510
Deflection at rupture, %	2.572	3.698
Modulus at rupture, lb/(in/in)	884.1	1.423

K49 SPOOL 1708 Q.A. BASELINE

Test ID	Max. Load,Lb	Strain at Max, %
2015021	19.54	2.182
2015022	20.68	2.442
2015023	19.76	2.427
2015024	24.69	2.743
2015025	23.88	2.622
2015026	21.77	2.380
2015027	23.03	2.549
2015028	22.58	2.488
2015029	21.60	2.370
2015030	21.59	2.389
2015031	22.70	2.464
2015032	23.41	2.573
2015033	21.81	2.418
2015034	23.67	2.588
2015035	22.70	2.433
2015036	24.06	2.648
2015037	23.59	2.542
2015038	22.15	2.460
2015039	24.17	2.593
2015040	23.69	2.621

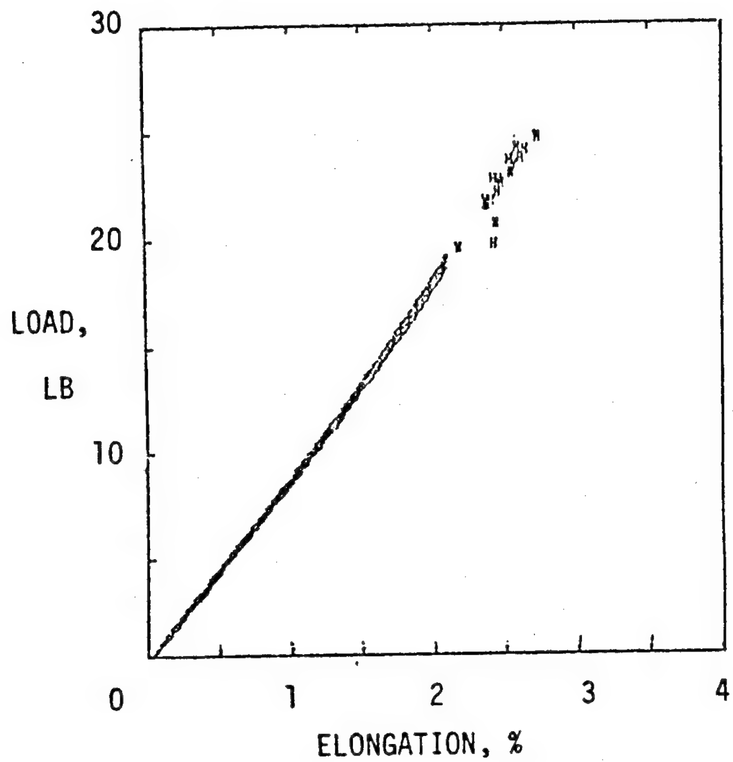

Fig. D2: Composite curve for Spool 1708 coated strands, 20 specimens. Group statistics are:

Property	Mean	CV,%
Rupture load, lb	22.55	6.305
Deflection at rupture, %	2.497	5.065
Modulus at rupture, lb/(in/in)	907.1	3.043

K49 SPOOL 3208 Q.A. BASELINE

Test ID	Max. Load,Lb	Strain at Max, %
2015041	22.06	2.725
2015042	26.12	3.091
2015043	22.89	2.787
2015044	23.75	2.868
2015045	23.22	2.819
2015046	24.10	2.897
2015047	22.25	2.728
2015048	19.80	2.336
2015049	22.67	2.721
2015050	21.74	2.569
2015051	20.09	2.244
2015052	23.14	2.658
2015053	22.08	2.522
2015054	19.84	2.295
2015055	22.68	2.504
2015056	22.07	2.688
2015057	25.34	3.085
2015058	21.91	2.599
2015059	21.32	2.624
2015060	21.18	2.537

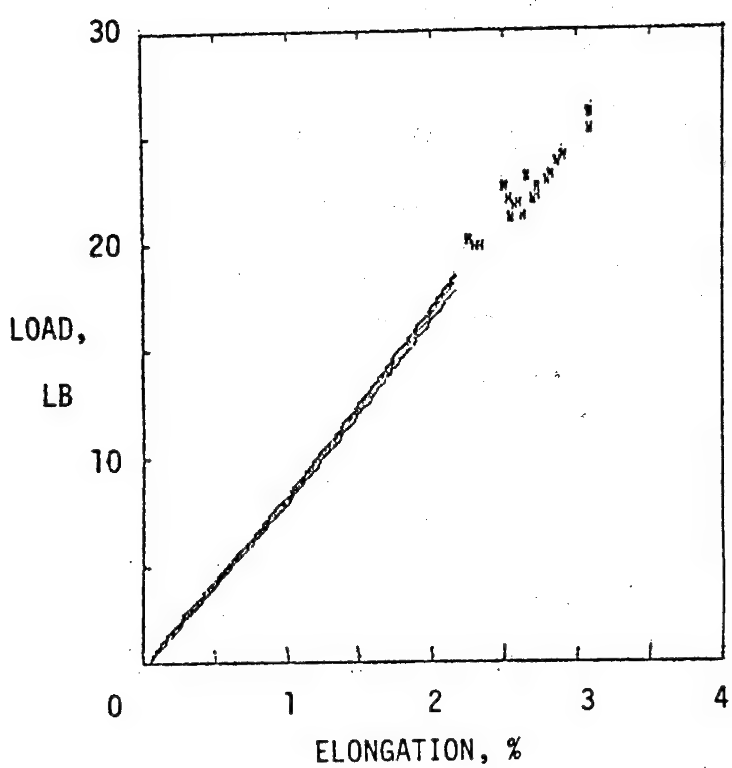

Fig. D3: Composite curve for Spool 3208 coated strands, 19 specimens. Group statistics are:

Property	Mean	CV,%
Rupture load, lb	22.43	7.502
Deflection at rupture, %	2.862	8.952
Modulus at rupture, lb/(in/in)	844.0	3.178

K49 SPOOL 4938 Q.A. BASELINE

Test ID	Max. Load,Lb	Strain at Max, %
2015061	22.59	2.645
2015062	22.27	2.569
2015063	22.21	2.595
2015064	22.00	2.634
2015065	23.00	2.723
2015066	22.73	2.721
2015067	22.54	2.602
2015068	21.48	2.495
2015069	21.97	2.531
2015070	22.03	2.559
2015071	23.64	2.752
2015072	22.63	2.529
2015073	23.54	2.697
2015074	20.25	2.279
2015075	22.33	2.598
2015076	23.99	2.807
2015077	23.14	2.687
2015078	22.42	2.576
2015079	23.61	2.742
2015080	23.60	2.721

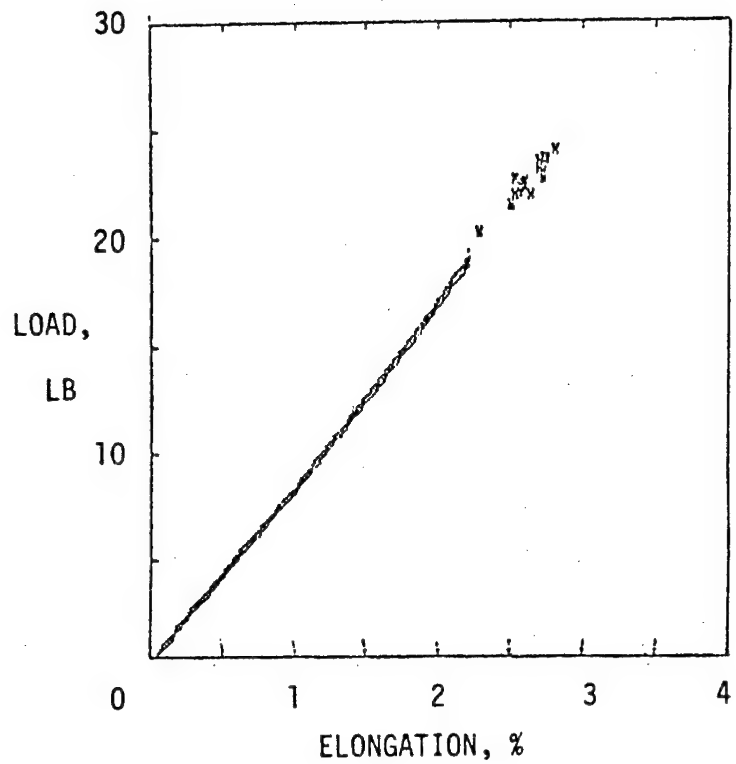

Fig. D4: Composite curve for Spool 4938 coated strands, 19 specimens. Group statistics are:

Property	Mean	CV,%
Rupture load, lb	22.50	3.989
Deflection at rupture, %	2.521	4.650
Modulus at rupture, lb/(in/in)	862.5	1.707

K49 SPOOL 7920 BASELINE AT RM. TEMP.

Test ID	Max. Load,Lb	Strain at Max, %
1928035	22.48	2.681
1928036	19.72	2.367
1928037	21.86	2.636
1928038	21.91	2.624
1928039	20.34	2.472
1928040	24.97	2.970
1928041	22.20	2.624
1928042	20.44	2.444
1928043	21.61	2.584
1928044	19.37	2.322
1928045	22.08	2.637
1928046	22.55	2.697
1928047	20.54	2.457
1928048	20.70	2.517
1928049	22.07	2.646
1928050	20.96	2.511
1928051	22.89	2.737
1928052	22.54	2.709
1928053	24.22	2.872
1928054	24.02	2.898
1928055	21.10	2.543
1928056	20.75	2.473
1928057	23.89	2.854
1928058	22.47	2.703
1928059	21.97	2.603
1928060	21.77	2.648
1928061	22.31	2.671
1928062	22.47	2.689
1928063	22.75	2.700
1928064	20.92	2.496
1928065	24.09	2.866
1928067	20.70	2.475
1928068	25.16	2.983
1928070	22.02	2.640
1928071	23.35	2.794
1928073	22.67	2.700
1928074	22.05	2.633

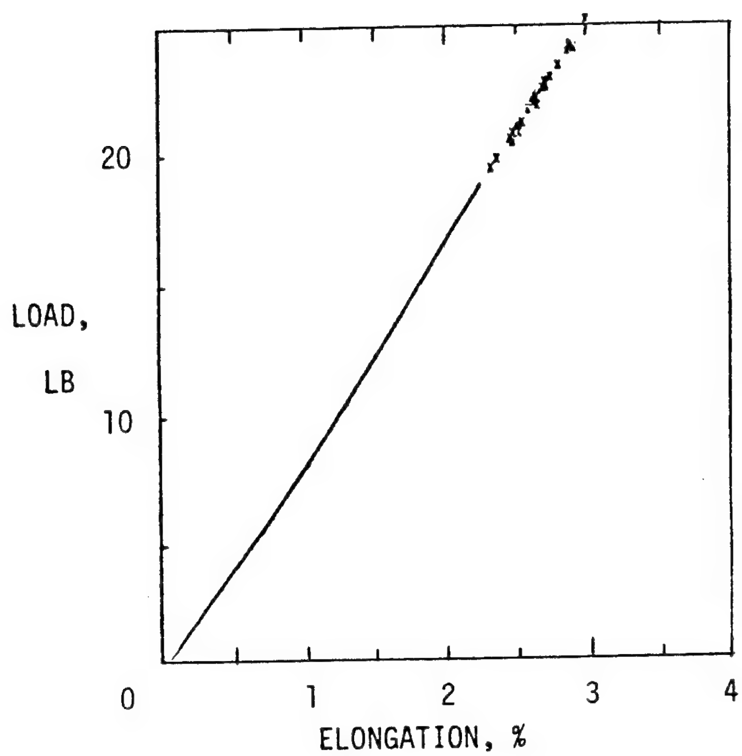

Fig. D5: Composite curve for Spool 7920 coated strands, 37 specimens. Group statistics are:

Property	Mean	CV,%
Rupture load, lb	22.11	6.221
Deflection at rupture, %	2.645	5.970
Modulus at rupture, lb/(in/in)	835.6	0.674

APPENDIX E

MANUFACTURERS IDENTIFICATION OF Y-12 AND LLNL KEVLAR SPOOLS

LLNL SISTER SPOOLS

Spool ID	Spinning ID	Finishing ID	Comments	
7473-00-3803	649-205-0400	205-280-1400		Sent LLNL
7473-00-2307	706-284-0245	245-287-0500	S2	Sent LLNL
7473-00-3213	706-284-0145	245-287-0700	S2	Sent LLNL
7473-00-6111	707-252-1700	226-261-2130	S2	
7473-00-5825	707-252-1700	226-261-2345	S2	Sent LLNL
7473-00-4731	707-279-0815	203-282-1615	S3	
7473-00-4544	707-279-0815	203-282-1815	S3	Sent LLNL
7473-00-6404	707-279-0815	203-282-2015	S3	
7473-00-7908	707-284-1800	233-287-2300	S2	Sent LLNL
7473-00-6607	707-284-1800	233-288-0100	S2	
7473-00-6126	708-252-1700	207-261-2200	S3	Sent LLNL
7473-00-6734	708-252-1700	207-262-0015	S3	
7473-00-3432	708-252-1700	207-262-0215	S3	
7473-00-8427	708-258-1245	247-263-2100	S2	
7473-00-7604	708-258-1245	247-263-2300	S2	Sent LLNL
7473-00-2508	710-264-2200	207-276-1530	S2	
7473-00-5128	710-264-2200	207-276-1700	S2	Sent LLNL
7473-00-2718	710-273-0800	241-286-1400	S3	Sent LLNL
7473-00-1525	710-273-0800	241-286-1630	S3	
7473-00-2732	710-273-0800	241-286-1800	S3	
7473-00-2819	710-284-0245	218-287-0500	S3	
7473-00-3208	710-284-0245	218-287-0700	S3	Sent LLNL
7473-00-3208	710-284-0245	218-287-0700	S3	Sent LLNL
7473-00-4139	710-284-0245	218-287-1000	S3	
7473-00-5401	712-277-0120	248-283-1430	S2	Sent LLNL
7473-00-3048	712-277-0120	248-283-1650	S2	
7473-00-6520	718-264-2500	204-284-2246	S2	Sent LLNL
7473-00-6828	718-264-1500	204-284-1880	S2	
7473-00-0242	719-284-0145	227-287-0500		Sent LLNL

Spool ID	Spinning ID	Finishing ID	Comments
7473-00-1742	721-267-0700	206-275-2100	S2
7478-00-5205	721-267-0700	206-275-2300	S2 Sent LLNL
7473-00-3543	722-267-2200	223-276-2130	S3 Sent LLNL
7473-00-8221	722-267-2200	223-276-2330	S3
7473-00-4034	722-267-2200	223-277-0150	S3
7473-00-0636	723-259-1630	214-262-0515	S3 Sent LLNL
7473-00-1030	723-259-1630	214-262-0715	S3
7473-00-7736	723-259-1630	214-262-0945	S3
7473-00-1147	723-265-2015	228-274-1700	S2 Sent LLNL
7473-00-1122	723-265-2015	228-274-2100	S2
7473-00-5542	730-284-0400	208-286-2300	Sent LLNL
7473-00-4938	732-268-0615	209-276-1330	S3 Sent LLNL
7473-00-2510	732-268-0615	209-276-1530	S3
7473-00-6923	732-268-0615	209-276-1700	S3
7473-00-0922	732-283-0745	233-285-0100	S3
7473-00-0728	732-283-0745	233-285-0300	S3 Sent LLNL
7473-00-0718	732-283-0745	233-285-0500	S3
7473-00-2929	733-267-1745	205-277-0945	Sent LLNL
7473-00-7001	733-267-1745	231-276-0430	
7473-00-0138	733-287-0630	219-287-2100	S3
7473-00-7932	733-287-0630	219-287-2300	S3 Sent LLNL
7473-00-6636	733-287-0630	219-288-0100	S3
7473-00-5805	734-259-2215	209-261-1800	Sent LLNL
7473-00-2626	735-264-1215	228-275-1030	S3
7473-00-7042	735-264-1215	228-275-1230	S3 Sent LLNL
7473-00-3734	735-264-1215	228-275-1500	S3
7473-00-5213	741-269-0900	225-276-0430	S3
7473-00-5233	741-269-0900	225-276-0630	S3 Sent LLNL

Spool ID	Spinning ID	Finishing ID	Comments	
7473-00-1843	741-269-0000	225-276-0830	S3	
7473-00-3519	742-267-1930	248-276-2130	S2	
7473-00-8234	742-267-1930	248-276-2330	S2	Sent LLNL
7473-00-2648	742-270-0730	212-275-1030	S3	
7473-00-7043	742-270-0730	212-275-1230	S3	
7473-00-3744	742-270-0730	212-275-1500	S3	Sent LLNL
7473-00-7229	743-262-0300	209-282-2330	S3	
7473-00-2913	743-262-0300	209-283-0230	S3	
7473-00-7520	743-262-0300	209-283-0330	S3	Sent LLNL
7473-00-0124	743-285-1745	232-287-2100	S3	Sent LLNL
7473-00-7905	743-285-1745	232-287-2300	S3	
7473-00-6602	743-285-1745	232-288-0100	S3	
7473-00-5933	744-265-0730	238-278-0100	S2	
7473-00-5607	744-265-0730	238-278-0320	S2	Sent LLNL
7473-00-1234	744-266-1030	243-275-0150	S3	
7473-00-0315	744-266-1030	243-275-0315	S3	
7473-00-1224	744-266-1030	243-275-0615	S3	Sent LLNL
7473-00-6039	744-285-1745	241-287-1400		Sent LLNL
7473-00-3920	745-259-2115	217-261-1800		
7473-00-3918	745-259-2115	225-261-1730		Sent LLNL
7473-00-4914	745-267-0130	208-276-0500	S2	
7473-00-1703	745-267-0130	208-276-0700	S2	Sent LLNL
7473-00-7920	745-286-2030	206-287-2300	S2	Sent LLNL
7473-00-6605	745-286-2030	206-288-0100	S2	
7473-00-3222	746-279-1830	215-236-1400	S3	Sent LLNL
7473-00-1543	746-279-1830	215-236-1540	S3	
7473-00-2725	746-279-1850	215-286-1800	S3	
7473-00-8310	746-280-0200	246-282-0700	S3	Sent LLNL

Spool ID	Spinning ID	Finishing ID	Comments
7473-00-2346	746-280-0200	246-282-0845	S3
7473-00-6423	746-280-0200	246-232-1030	S3
7473-00-7112	747-278-0045	211-279-1230	S2
7473-00-2115	747-278-0045	211-279-1500	S2 Sent LLNL
7473-00-22278	748-252-0030	223-262-2300	S2 Sent LLNL
7473-00-8034	748-252-0030	223-263-0300	S2
7473-00-7035	748-270-0730	202-275-1230	S2
7473-00-3748	748-270-0730	202-275-1500	S2 Sent LLNL

NOTE: The meaning of numbers in listing:

Example: Spool ID

7473-00-3743
- 37 = Box number
- 43 = Location in box

748-270-0730
- 270 = Day of year
- 0730 = Hour of day

202-275-1500
- 275 = Day of year
- 0730 = Hour of day

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